GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L24S10, doi:10.1029/2007GL031627, 2007

3D global multi-species Hall-MHD simulation of the Cassini T9 flyby

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Received 21 August 2007; revised 12 October 2007; accepted 24 October 2007; published 1 December 2007.

[1] The wake region of Titan is an important component of Titan's interaction with its surrounding plasma and therefore a thorough understanding of its formation and structure is of primary interest. The Cassini spacecraft passed through the distant downstream region of Titan on 18:59:30 UT Dec. 26, 2005, which is referred to as the T9 flyby and provided a great opportunity to test our understanding of the highly dynamic wake region. In this paper we compare the observational data (from the magnetometer, plasma analyzer and Langmuir probe) with numerical results using a 7-species Hall MHD Titan model. There is a good agreement between the observed and modeled parameters, given the uncertainties in plasma measurements and the approximations inherent in the Hall MHD model. Our simulation results also show that Hall MHD model results fit the observations better than the non-Hall MHD model for the flyby, consistent with the importance of kinetic effects in the Titan interaction. Based on the model results, we also identify various regions near Titan where Hall MHD models are applicable. **Citation:** Ma, Y.-J., et al. (2007), 3D global multi-species Hall-MHD simulation of the Cassini T9 flyby, *Geophys. Res. Lett.*, *34*, L24S10, doi:10.1029/2007GL031627.

1. Introduction

[2] Titan has an extensive atmosphere/ionosphere system [*Hartle et al.*, 1982; *Nagy and Cravens*, 1998] with no appreciable intrinsic magnetic field [*Ness et al.*, 1982; *Backes et al.*, 2005]. Titan's orbit is at 20 R_S (R_S is the radius of Saturn) from Saturn and is located inside Saturn's magnetosphere for nominal solar wind conditions. Titan's interaction with the Saturnian magnetospheric plasma flow is similar in many ways to the solar wind interaction with Venus/Mars, but normally with subsonic rather than supersonic boundary conditions. The interaction process has been studied based on observations from both Voyager and Cassini [*Hartle et al.*, 1982, 2006a, 2006b; *Hartle and Sittler*, 2007; *Sittler et al.*, 2005] and also by various numerical models [*Ledvina and Cravens*, 1998; *Kabin et al.*, 1999; *Brecht et al.*, 2000; *Nagy et al.*, 2001; *Kallio et al.*, 2004; *Ma et al.*, 2004, 2006; *Backes et al.*, 2005; *Sillanpää et al.*, 2006; *Simon et al.*, 2006, 2007].

[3] On the upstream side, Saturn's magnetospheric plasma flow starts to slow down from about 8 R_T (Titan radius) due to mass loading with Titan's extended atmosphere [*Hartle at al.*, 2006a, 2006b], while significant pile-up and strong draping of the magnetic field lines begins around 2 to 3 R_T in front of the satellite. In the tail region, an induced bipolar magnetic tail was observed by Voyager spacecraft and three thin current regions were crossed [*Ness et al.*, 1982]. A clear tail structure was seen by the Cassini TA, TB and T3 observations [*Backes et al.*, 2005; *Neubauer et al.*, 2006], as the magnetic field reversed direction suddenly when Cassini passed from one magnetic tail lobe to the other. The wake region is highly dynamic, and both the location and width of the current sheet are closely related to the upstream plasma pressure and magnetic field directions.

[4] The Cassini spacecraft passed through the downstream wake of Titan on 18:59 UT Dec. 26, 2005, and this pass is referred to as the T9 flyby. As shown in Figure 1, the trajectory was located approximately in Saturn's equatorial plane. The color in the plot shows contours of the cosine of the solar zenith angle (SZA). The spacecraft approached Titan from the sunlit side during the inbound portion of the flyby. Titan was located at about 3 Saturn local time (SLT) during the flyby, which indicates that, if the incoming flow is along the ideal corotation direction, the upstream side corresponds approximately to the nightside of Titan's ionosphere. The closest approach altitude was approximately 10409 km (4.0R_T). In this paper, we describe our simulation results using input parameters constrained by magnetometer and plasma observations [*Dougherty et al.*, 2004; *Young et al.*, 2004; *Gurnett et al.*, 2004].

2. Model Description

[5] The model that we are using is a multi-species MHD model, described in some detail by *Ma et al.* [2004, 2006]. One major advantage of the multi-species model is its ability to treat the different mass of each ion species of interest. Our model solves continuity equations for 7 pseudo ion species as listed by *Ma et al.* [2004, 2006]; the calculation of densities of each ion species takes into account the major chemical reactions including photoionization, impact ionization, charge exchange and recombination self-consistently. In addition, the photoionization rates used are dependent on the Solar Zenith Angle (SZA). In our model, we assume that all the ion species share the same

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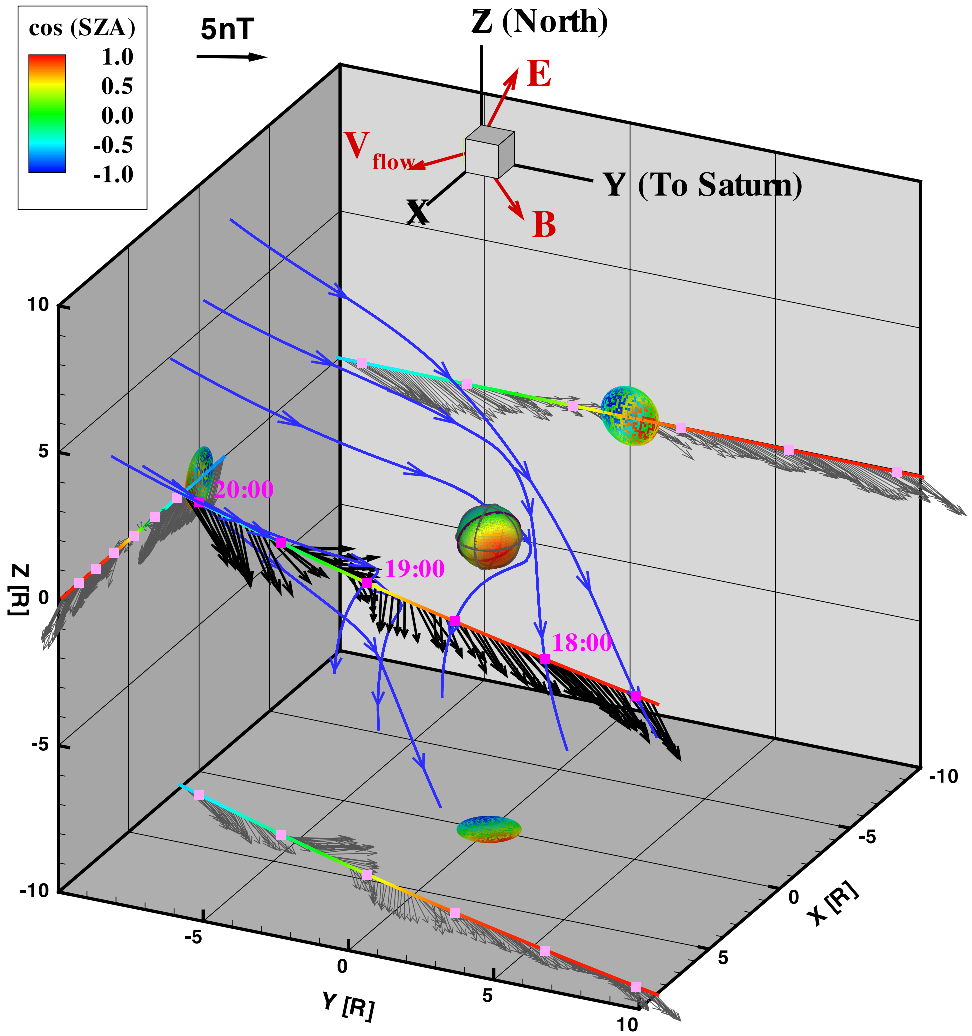

Figure 1. Colors show cosine of Solar Zenith Angle (SZA). The vectors show observed magnetic field from the magnetometer. The projections of the trajectory and magnetic field into three vertical planes are also shown. The three red arrows show upstream flow direction (V flow), magnetic field (B), and convection electric field (E) direction respectively. The blue lines are magnetic field lines traced from the simulation results along the trajectory from 17:30 UT to 20:00 UT.

velocity and temperature. The major improvement of the model is the inclusion of Hall effect, which we briefly outline next.

[6] The Hall effect becomes important when the ion gyroradii are comparable to the gradient scale size, which is true for Titan. The gyroradii of heavy ion species (such as O^{+}or CH$_4^{+}$) in the outer magnetosphere were found to be ∼5000 km [*Hartle et al.*, 1982; *Sittler et al.*, 2005]. So the use of the Hall MHD model is more appropriate for the present study. The magnetic induction equation, which includes the Hall effect, can be expressed as:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{u} \times \mathbf{B} - \frac{\mathbf{J}}{ne} \times \mathbf{B} - \eta \mathbf{J} \right) \qquad (1)$$

where n is total ion number density and e is electron charge. All the other variables have their conventional meanings. The three terms on the right hand side of the equation are the convection term, Hall term and diffusion term respectively. The inclusion of the Hall term allows the ions and electrons to move at different velocities. The magnetic field lines are still frozen to the electrons, but when there is a significant current, the "frozen-in" condition between ions and magnetic field lines is broken. Strictly speaking, the Hall MHD model is still limited by its fluid assumption, but it captures more essential physics than ideal or resistive MHD.

[7] The reference frame is in the Titan Interaction System (TIIS) [*Backes et al.*, 2005]. The computational domain is set as: $-32R_T \le X \le 96R_T$, $-64R_T \le Y, Z \le 64R_T$, and R_T is taken to be 2575 km. We are using a spherical grid structure. The radial resolution ranges logarithmically from 34 km at the inner boundary (725 km) to 6862 km (∼2.7R_T) near to the outer boundary. The angular resolution is 2.5^0 below 1 R_T and 5.0^0 above that altitude. The total number of grid cells is 1,057,536.

[8] The upstream electron density is chosen to be 0.06/cc according to CAPS (Cassini Plasma Science) observation. CAPS reports only light ions (H$^+$) in the upstream plasma (F. Crary, private communication, 2007). But the simulations

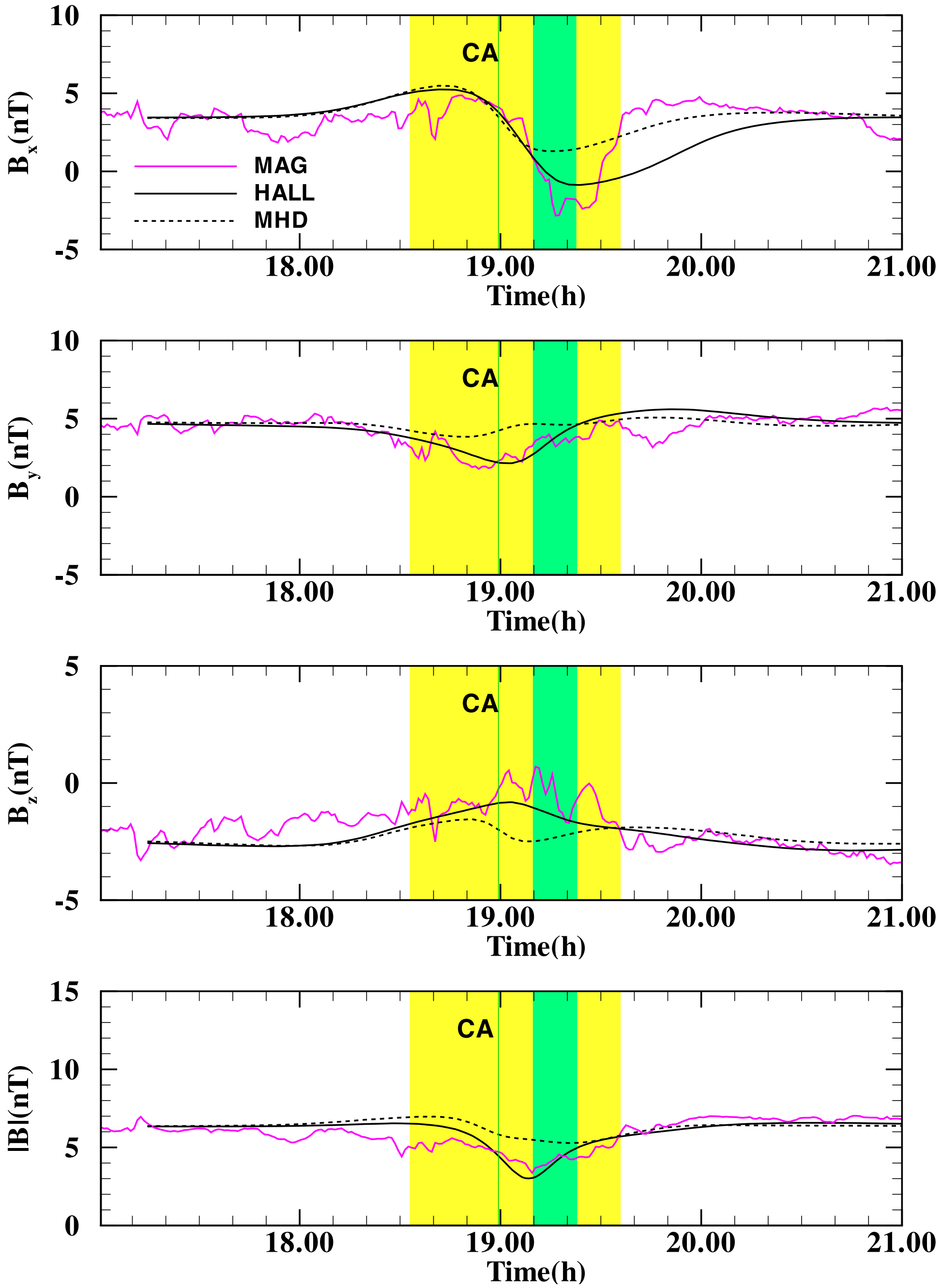

Figure 2. Model and data comparison of magnetic field along T9 flyby. The green lines indicate the closest approach time, while the green and yellow regions are corresponding to different range of ion gyroradii as shown in Figure 4.

with only light component could not reproduce the observed plasma features. So in our calculation, we assume that the plasma consists of 50% light ion species (H^+) and 50% median ion species (e.g. CH_4^+ or O^+). The plasma velocity is set to 120 km/s, this value is close to the average value of plasma flow speed from CAPS (the direction of the flow will be discussed in more details in the next section) and the upstream magnetic field is taken as (3.4, 4.9, −2.3) nT based on the average observational data from MAG (magnetometer). The plasma temperature is set to 2.0 KeV similar to Voyager measurements. (Note: the ratio of the temperatures between electron and ions varies with locations and time, thus $T_i = T_e$ is a commonly used assumption in MHD models.) Those parameters correspond to a subsonic (Ms = 0.54) and subalfvenic (Ma = 0.54) plasma flow with plasma $\beta = 1.2$.

3. Simulation Results and Comparisons with Observations

[9] Figure 2 shows the comparison between the calculated and observed magnetic field values along the T9 trajectory for plus and minus 2 hours of closest approach (CA), which is indicated by the green lines. The observed values from MAG are plotted in purple, while the model results

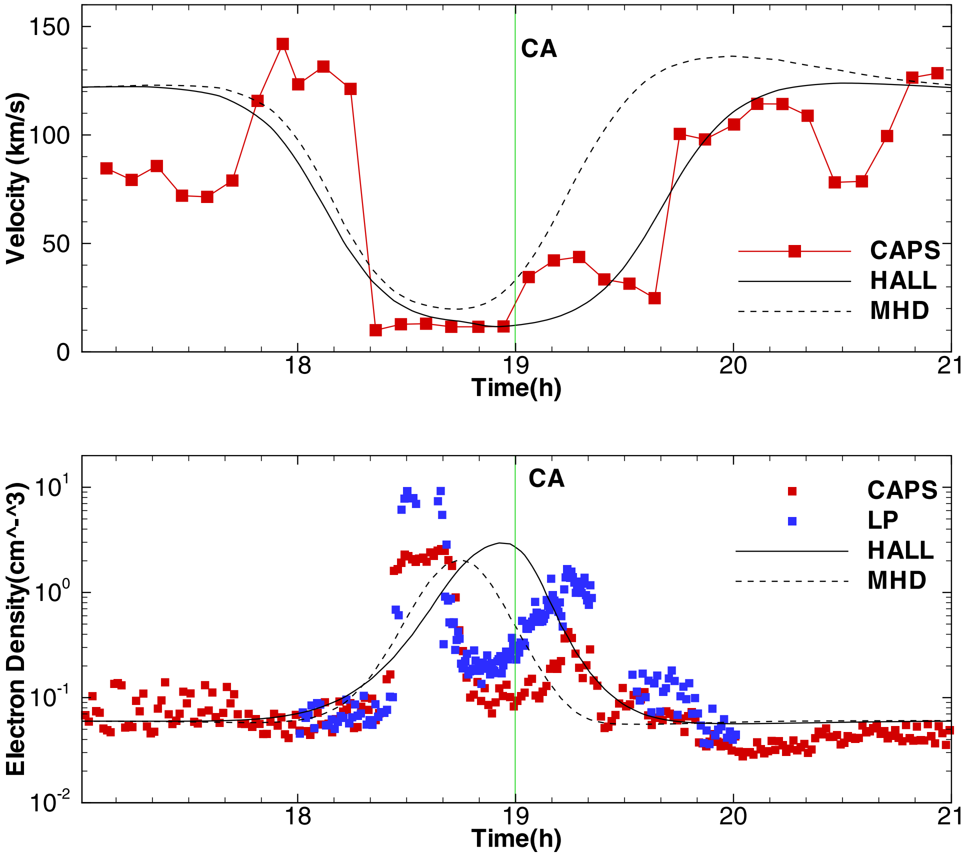

Figure 3. Plasma velocity and electron number density along the flyby trajectory for model results and plasma analyzer, Langmuir probe observations.

from Hall MHD model are shown by solid black lines. The dashed black lines show simulation results from the resistive MHD calculations, as a reference. Significant changes of the magnetic field take place between 19:00 and 19:40. B_X changes sign rapidly as the spacecraft passes through the current sheet [*Wei et al.*, 2007]. The overall trends of magnetic field vectors, especially the sharp decrease of B_X, are reasonably well reproduced by the Hall MHD model. However, the predicted B_X component increases slightly before 19:00 UT, while there is no obvious increase seen in the observations. The missing lobe from the observation may be related to the cold plasma observed during that period. The steepness of the dip in the B_X component is closely related to the mass density of the upstream plasma and the model predicts a much smaller drop of the B_X component when we assume that the upstream flow is only composed of light ions.

[10] Our simulation results also show that a different upstream flow direction would result in a different time for the drop of the B_X component while the magnitudes of the magnetic field distortions are not affected by the flow direction significantly. There is no accurate measurement of the upstream flow direction because the flow is out of the field of the view of CAPS during the beginning of the flyby [*Szego et al.*, 2007]. When we assume that the flow is along the ideal corotational direction, the calculated reversal of the magnetic field is about 15 minutes earlier than observations indicate. When the upstream flow is tilted relative to the X axis with an angle of about 30 degrees in the direction away from Saturn, the simulation results predicts the sharp decrease of B_X at almost the same time as observed. This angle is smaller than the CAPS estimate of, >40 degree [*Szego et al.*, 2007] and slightly smaller than 36 degree as calculated by *Bertucci et al.* [2007] based on MAG observations.

[11] A comparison between the calculated and observed plasma parameters is shown in Figure 3, during the 4-hour interval centered on the closest approach (CA). The observed values from CAPS are plotted in red, from Langmuir Probe (LP) are plotted in blue, while the model results are shown by black lines. Figure 3 (top) shows a good agreement between the calculated plasma velocities and that from the CAPS measurements. The lower panel shows the comparison of the calculated electron density along with the LP and CAPS observations.

[12] The model predicts only a single density peak, as compared with the double density peaks observed by both the CAPS and the LP. The predicted electron density peak location is in the middle of the observed double peaks, and the simulated peak density is of the same order as the measured values. Also it is interesting to note that the first density peak period occurs around 18:30 UT, while the encounter of the tail region, as indicated by the magnetic field observation, starts at 19:00UT. LP data [*Modolo et al.*, 2007] show that the dense plasma in the region was also cold (∼2 eV) compared with the ambient plasma (electron energy range ∼200 ev). This slowly moving plasma observed before any significant disturbance of the magnetic field is likely to be associated with a non-Maxwellian

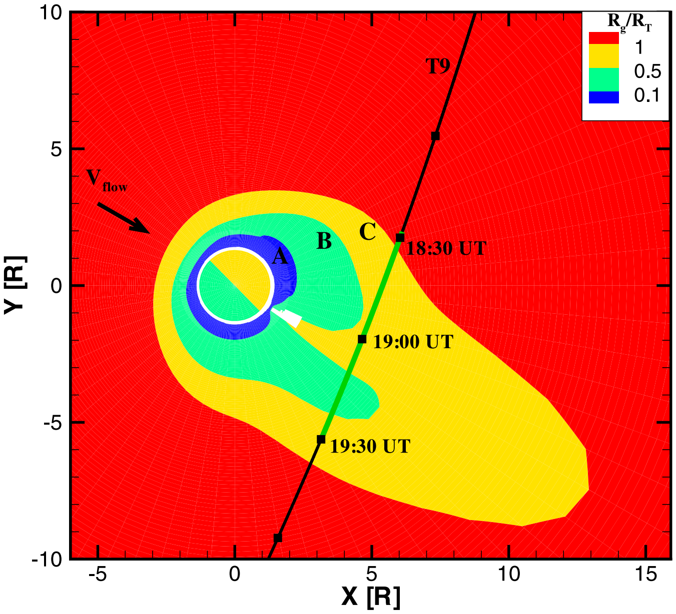

Figure 4. Contour plot of Rg/RT, the ratio of the gyroradii of heavy ions (mass 16) and Titan radius in the equatorial (X-Y) plane. Regions A, B, and C correspond to region with gyroradii less than 0.1, 0.5, and 1 respectively. The green color along the trajectory of T9 shows the main interaction region for this flyby. The inner boundary (725 km altitude, ~1.28 RT) of the model is also shown; with the yellow and cyan color showing the sunlit and night side, respectively.

velocity distribution and thus cannot be explained through a fluid assumption. Also the field lines that we created from our MHD model results along the trajectory (see Figure 1) indicated that the plasma probably originated from Titan's ionosphere. This is also suggested by the studies of both *Wei et al.* [2007] and *Kallio et al.* [2007]. A test particle model using the field lines created by MHD model may be able to reproduce the splitting features of the electron density distribution better.

4. Discussion and Summary

[13] It is important to understand why the Hall MHD model results fit the observations fairly well even when the ion gyroradii of the upstream plasma is larger than Titan's size. For this flyby, the gyroradii of the heavy ion species (mass 16) are about 1.5 R_T. The fluid model describes the plasma at any location with three parameters: density, velocity and temperature. The concept of temperature only makes sense when the plasma components are not far from local thermodynamic equilibrium. When the ion gyro-radius is large, ion thermal velocity distribution could be far from a Maxwellian distribution. Under such circumstances, the scalar pressure cannot be used; a full pressure tensor is needed to describe the pressure force that acts on the plasma. However the pressure force is close to zero in the unperturbed region far from Titan. It is also important to note that the ion gyroradius is not a constant near the interaction region, and it decreases quite significantly in the area close to Titan due to the pile-up of the magnetic field and the decrease of the ion temperature as results of mass loading and ion-neutral collision processes. Figure 4 shows the variation of the gyroradii of heavy ions (mass 16) in the equatorial plane. The plasma temperature from MHD model results is used to estimate the heavy ion temperature in the calculation of ion gyroradii. The inner boundary (725 km altitude, ~1.28 R_T) of the model is also shown in Figure 4, with the yellow and cyan color showing the sunlit and night side, respectively.

[14] The blue region (region A) shows the region where the gyroradii of heavy ions are at least an order of magnitude smaller than Titan's radius. In this region, $R_T > 10$ Rg, thus the MHD assumptions are valid. Region A is not symmetric about the flow direction as it is also affected by the direction of the solar EUV. The altitude of this region ranges from 1500 km in the upstream side to about 3500 km, and peaks in the dayside. Both Cassini Ta and Tb flybys passed this region, with closest altitude less than 1200 km, and MHD model results of *Backes et al.* [2005], *Ma et al.* [2006] and *Neubauer et al.* [2006] for the two flybys agreed with the observations quite well.

[15] Region B (cyan) shows where the gyroradii of heavy ions are less than half of Titan's radius. In this region, ions and electrons are not tightly coupled and the kinetic effect becomes important. Hall currents are necessary to be included in the MHD model to describe the system accurately. Most of the interaction regions of T9 as indicated by the green color along the trajectory, are in this region or very close. This is the reason that Hall MHD model results show good agreement with the observations (except for the comparison of the electron density; it is difficult to conclusively tell which model better reproduces the data). The better matching of Hall MHD model with the observations along the trajectory than the non-Hall MHD model confirms that kinetic effects are important in this region.

[16] Region C (with yellow color) and beyond region (red colored area) are the regions with gyroradii larger than 0.5 R_T. In this region, the kinetic effects become significantly important. However, most of the outer region is unperturbed with no pressure gradient force and the main interaction region is within the area, where the gyroradii is smaller than 1 R_T. Thus a fluid model can still give a reasonable first

order estimation of the global interaction structure. In region B and C, some kinetic effects (such as Hall currents) could be significant and there might be noticeable velocity/temperature differences between different ion species, which are neglected in the single fluid model. In this region hybrid/kinetic models are more appropriate, while multifluid models with anisotropic pressure taken into account should also do a fairly good job.

[17] Also there are two white colored regions in Figure 4. Those regions are cut off because they are either below the ionospheric peak region or inside the current sheet of the tail. In those areas, the magnitude of the magnetic field is quite weak while both the ion and neutral densities are relative high. Thus collisions are quite important in these regions and the fluid assumption is safe. Please also keep in mind that the boundaries of those regions are not fixed, but tightly related with upstream condition and to Titan's relative location in the Saturnian system. The hybrid simulations also show similar trends of the decreasing of ion gyroradii in the interaction region near Titan (R. Modolo, private communication, 2007).

[18] In summary, we have presented model results for the Cassini T9 flybys of Titan and compared them with the observations. The agreements are good between the observed and modeled parameters, considering the uncertainties in the plasma measurements, possible variations of the upstream conditions as well as the approximations associated with the Hall MHD model. The major features of the interaction are reasonably well reproduced by the Hall MHD model, indicating the importance of kinetic effects in the interaction process, while certain features, such as the observed splitting features of the plasma density are surely beyond the limitations associated with the fluid assumption. More kinetic effects such as electron heat conduction and anisotropic plasma pressure will be considered in a future study to improve the modeling of the interactions.

[19] **Acknowledgments.** The work presented here was supported by NASA/JPL contract 1279285, NSF grant ATM-0455729 and NASA grant NNG06GF31G. Gabor Toth received partial support from OTKA grant T047042.

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